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DEVELOPMENT OF A FRESNEL LENS CONCENTRATOR FOR SPACE APPLICATION*

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EXTENDED ABSTRACT

Since 1977, ENTECH (including its predecessor organization, E-Systems Energy Technology Center) has been actively developing, refining, and commercializing Fresnel lens photovoltaic concentrator systems for terrestrial applications. These systems are all based on a unique, transmittance-optimized, error-tolerant, Fresnel lens optical concentrator, which has been patented in fifteen countries (e.g., U.S. Patent No. 4,069,812). Much of this terrestrial development effort has been carried out as part of the Department of Energy's National Photovoltaic Program, under the Photovoltaic Concentrator Project administered by Sandia National Laboratories in Albuquerque. A typical ENTECH line-focus silicon cell concentrator array is shown in Figure 1. The first major installation of this type of equipment is represented by the 25 KWE system at DFW Airport's Central Utility Plant. This system has operated efficiently and reliably since 1982. Using low-cost, 15% efficient, linear Fresnel lens/polycrystalline silicon concentrator modules, ENTECH is currently offering utility-scale terrestrial systems at prices approaching $3 per peak DC watt, about one-third the price of terrestrial flat-plate photovoltaic systems.

In early 1986, ENTECH was selected under NASA's Small Business Innovative Research (SBIR) program, to perform a conceptual design study of a Fresnel lens photovoltaic concentrator system for space application, based on the successful terrestrial technology background described above. After evaluating both line-focus and point-focus approaches, ENTECH and NASA jointly selected a mini-dome lens point-focus concentrator with gallium arsenide cells (Figure 2) as near-optimal for space applications. The selected approach uses a square-aperture dome Fresnel lens (smooth exterior surface/prismatic interior surface) to focus incident sunlight onto a small gallium arsenide cell, which is mounted to a thin aluminum backplane radiator for cooling. The shape of the lens (defined in U.S. Patent No. 4,069,812) is non-spherical, such that solar rays make equal angles of incidence and emergence with each prism in the lens. This refractive symmetry minimizes reflection losses, sun image size, and the effects of aberrations and manufacturing inaccuracies. For example, the effect of slope errors (shape errors) is 200 times less for the dome lens than for any reflective concentrator. Using a simple aluminum "egg-crate" honeycomb structure, a matrix of individual concentrator modules can be combined into a larger panel (Figure 3). To allow panel stacking during transport, the honeycomb structure is slightly taller than the lens (Figure 4). Cells may be connected in any desired series/parallel arrangement to provide the proper current/voltage output.

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Panels can be combined to provide larger area assemblies (Figure 5). Finally, many panels can be integrated with a lightweight, automatically deployable structure, such as the Astro Aerospace Extendible Support Structure (ESS), to provide multi-kilowatt arrays (Figure 6). The dome lens concentrator (DLC) panel is remarkably light (Figure 7), weighing only 2.5 kg/sq.m. for the current design. With further optimization, this weight could easily be reduced. The ESS support structure is also light, weighing less than 0.7 kg/sq.m. of DLC panel aperture. Thus the total array weight for the current design is only 3.2 kg/sq.m., which is equivalent to the Space Station lightweight Kapton-blanket, planar-silicon array weight. Furthermore, the DLC honeycomb panel is extremely stiff structurally. Under 16g launch loads, maximum stresses correspond to a factor of safety of four. Under 1g terrestrial testing, maxiumum panel deflections correspond to panel slope errors of only 0.05 degree.

The key component of the DLC system is the mini-dome lens (Figure 8). While much work remains to be done in selecting the optimal lens material(s), the current leading candidate is Kel-F fluoropolymer. Kel-F has excellent optical properties, can be mass-produced into lenses by compression or injection molding, has a wide operating temperature range, and has an excellent outdoor lifetime in the terrestrial environment. However, for space applications, a protective coating (candidates: microglass, magnesium fluoride, silicon oxide, sol-gel, etc.) will be required to minimize degradation due to monatomic oxygen, ultraviolet radiation, particulate radiation, and other hostile environmental factors. The 3.7 cm square-aperture mini-dome lens has been sized for use with a 0.4 cm diameter gallium arsenide concentrator cell, since much effort has been expended over the past several years by NASA and its cell suppliers in developing such a cell for use at 100 sun irradiance. Without antireflection coatings, the selected lens (Figure 8) will provide 91.5% net optical efficiency. With a geometric concentration ratio (lens aperture area/cell active area) of 109X and an optical efficiency of 91.5%, a net irradiance of 100 suns will intercept the cell. Using a dispersive cone optics computer code, which has been validated through testing of several versions of terrestrial lenses, the dome lens design has been optimized to provide the desired focal plane irradiance profile. The individual prisms which comprise the lens have been designed to place the focussed sunlight onto a target area (0.26 cm diameter) which is smaller than the cell active area (Figure 9). The non-illuminated annular ring (0.07 cm in extent) around the edge of the target area has been sized to tolerate the lateral motion of the image in the event of a 1 degree sun-tracking error. Essentially no energy (less than 0.2%) is lost due to such a tracking error, by using this "guard band" lens design approach.

The selected cell design (Figure 10) is the same size and shape as the cell which has been developed by NASA for use in the TRW mini-Cassegrainian concentrator (MCC). However, for the dome lens application, the cell will utilize a parallel gridline geometry rather than a radial "wagon-wheel" gridline geometry. Also, the new cell will have 20% of its active area covered by gridlines, rather than the 14% coverage used in the MCC cell. By using a prismatic cell cover (the effectiveness of an example cover is shown in Figure 11 for a terrestrial line-focus silicon cell), the obscuration loss due to gridlines will be eliminated by redirecting incident sunlight onto active cell area between gridlines. The ability of the prismatic cell cover (patent pending) to eliminate gridline obscuration losses has been fully validated in tests at ENTECH, Sandia, and elsewhere, for several types of terrestrial cells. The performance parameters for the new prismatically covered cell (Figure 10) are based on measured cell parameters for a 1984-vintage Hughes gallium arsenide cell. The cell should provide a 24.7% conversion efficiency at 25C cell temperature under a uniform 100 sun irradiance. However, detailed cell modeling under the current program has shown that the cell performance will fall to 24.0% under the non-uniform irradiance produced by the lens (Figure 9). This decrease in performance is due to increased voltage drops in the emitter sheet, along the gridlines, and in the bulk material, due to the relatively high irradiance over the small illuminated cell area (Figure 9).

While a 1 degree maximum tracking error is anticipated by NASA for most space applications, larger tracking errors can be readily accommodated by making the cell active diameter slightly larger (Figure 12), i.e., by decreasing the geometric concentration ratio from 109X to lower values. For example, with a 26X geometric concentration ratio (0.82 cm active cell diameter), a 4 degree tracking error can be tolerated, while maintaining the overall lens/cell module efficiency above 21% at 25C cell temperature (Figure 12). Thus, with slight modification in cell size, very large tracking errors can be tolerated if mission requirements so dictate.

The conceptual design and thermal performance of the cell-to-radiator mount have also been investigated (Figure 13). By using a top-metallized, plasma-sprayed alumina mount, the cell-to-radiator temperature differential can be maintained at about 4C. The backplane radiator has also been thermally analyzed (Figure 14) to define the effect of radiator thickness on cell operational temperature. The thermal analysis results have been interpreted in terms of cell operational efficiency, by using the measured gallium arsenide efficiency/temperature coefficient (-0.035% per degree C), resulting in the selection of a 200 micron thick radiator as near-optimal (Figure 15). This thickness corresponds to a cell temperature of 100C, and a cell efficiency of 21.4%.

In summary, the selected conceptual design of the dome lens concentrator uses a 3.7 cm square aperture dome lens to focus onto a 0.4 cm active diameter gallium arsenide cell. The selected configuration will provide 91.5% lens optical efficiency and 21.4% cell efficiency at 100 suns irradiance and 100C cell temperature, for an overall lens/cell module efficiency of 19.6%. The selected configuration will tolerate 1 degree tracking errors with negligible loss of performance. The selected panel weight is 2.5 kg/sq.m. The selected ESS support structure weight is 0.7 kg/sq.m. These performance and weight parameters have been compared to state-of-the-art planar silicon and mini-Cassegrainian gallium arsenide arrays (Figure 16). In addition, improved versions of the three technologies have been included in the comparisons. For planar silicon, the major anticipated improvement in technology relates to a more efficient cell (8 cm square with chopped corners). For the Cassegrainian and dome lens concentrators, improved cell technology has recently been demonstrated by Varian, and improved optical performance is expected (higher reflectance Cassegrainian components and anti-reflection coatings for the lens). After including packing factor and wiring/mismatch losses for all three technologies, the dome lens concentrator clearly offers higher performance (w/sq.m.) and higher specific power (w/kg) than the planar silicon or Cassegrainian approaches, for both current and improved technology versions of the three approaches. With further development (i.e., multi-junction cells), the dome lens concentrator approach should provide 300 w/sq.m. in performance, and 100 w/kg in specific power. In final summary, the dome lens concentrator system represents an exciting new space power option.

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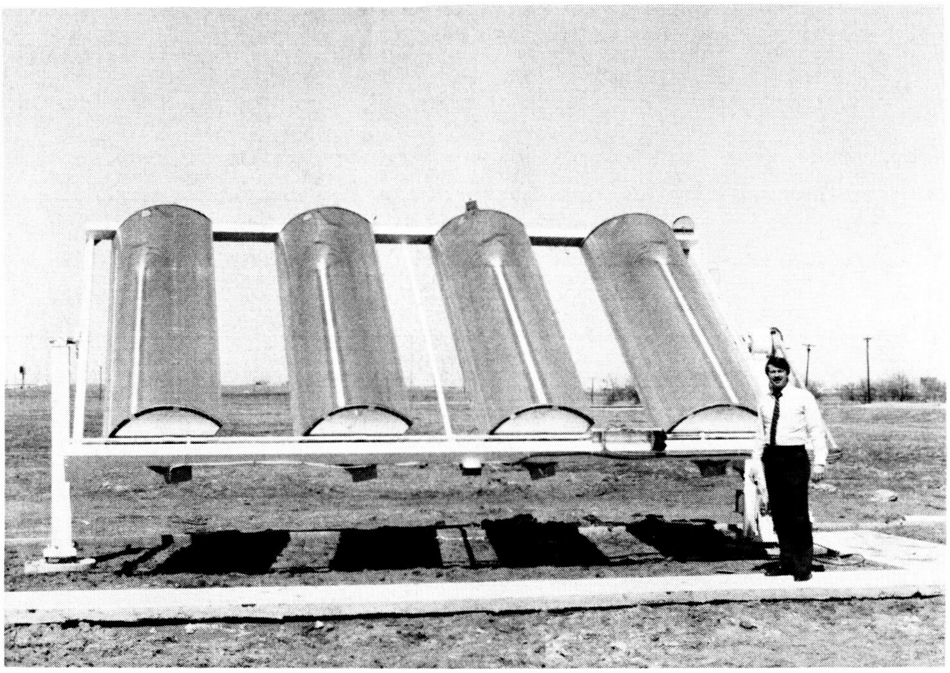


FIGURE 1 - TYPICAL ENTECH TERRESTRIAL PHOTOVOLTAIC CONCENTRATOR ARRAY

DOME LENS PV MODULE CONCEPTUAL DESIGN

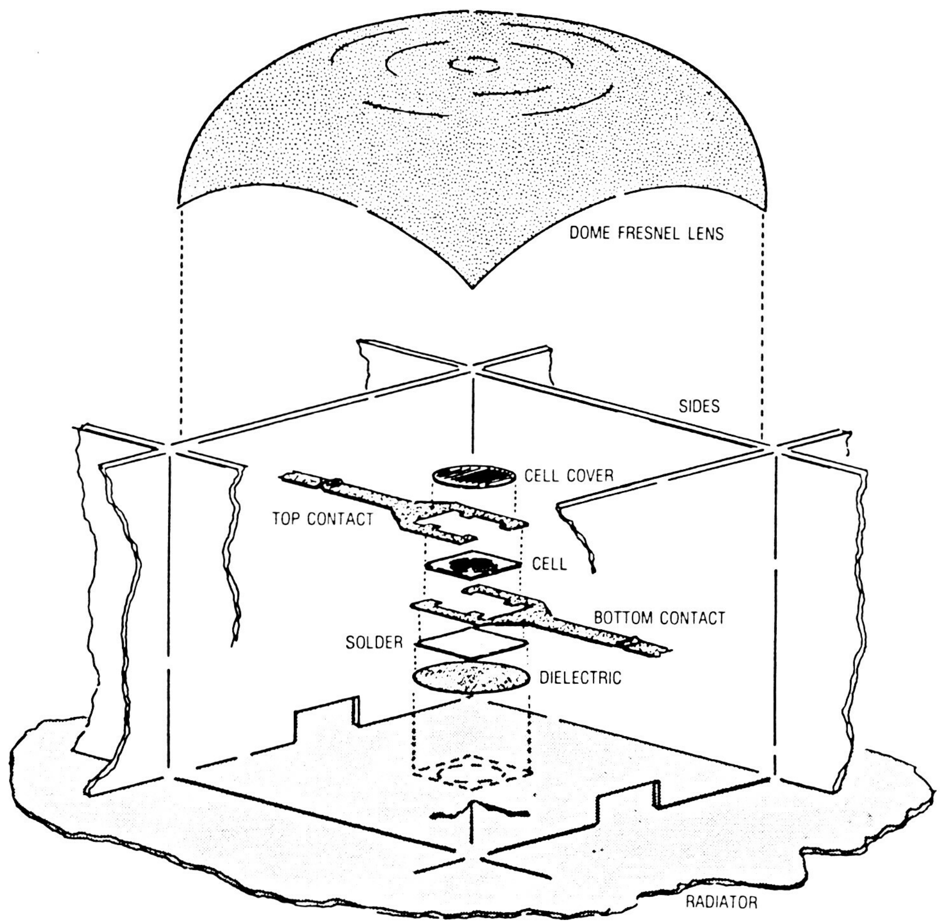


FIGURE 2

ENTECH DOME LENS PV CONCENTRATOR PANEL CONCEPTUAL DESIGN (1/4 PANEL)

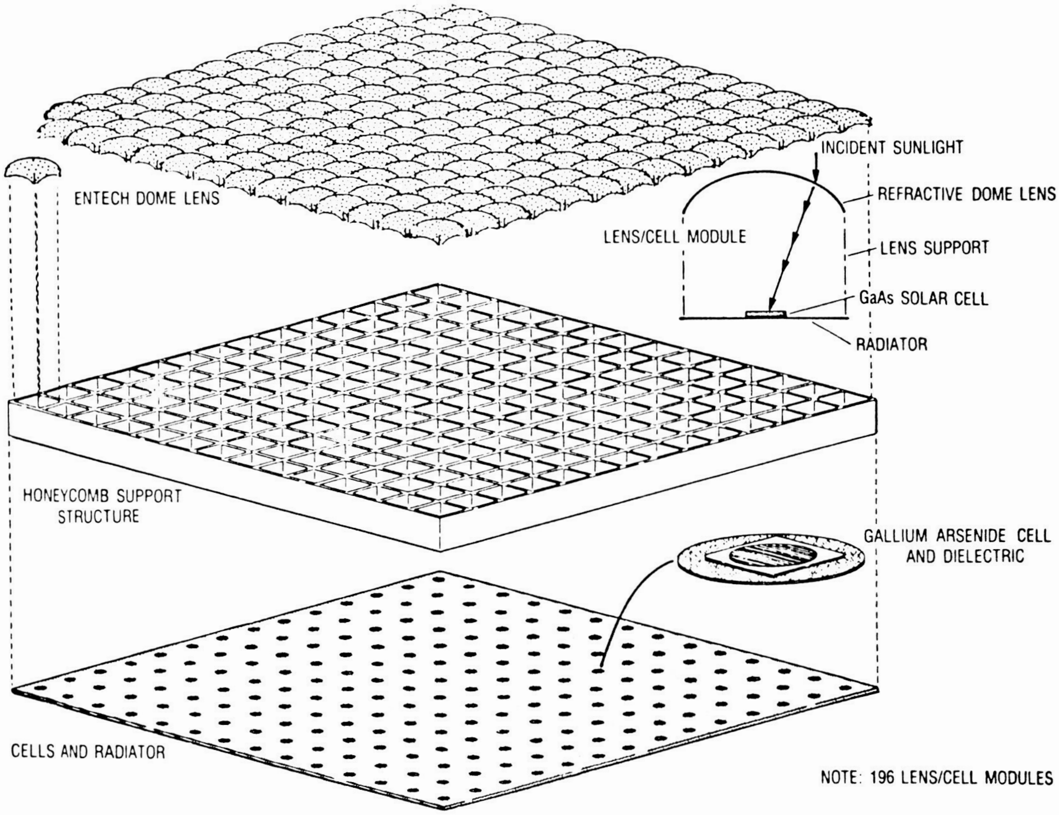


FIGURE 3

CROSS - SECTIONAL VIEWS OF DOME LENS PV PANEL

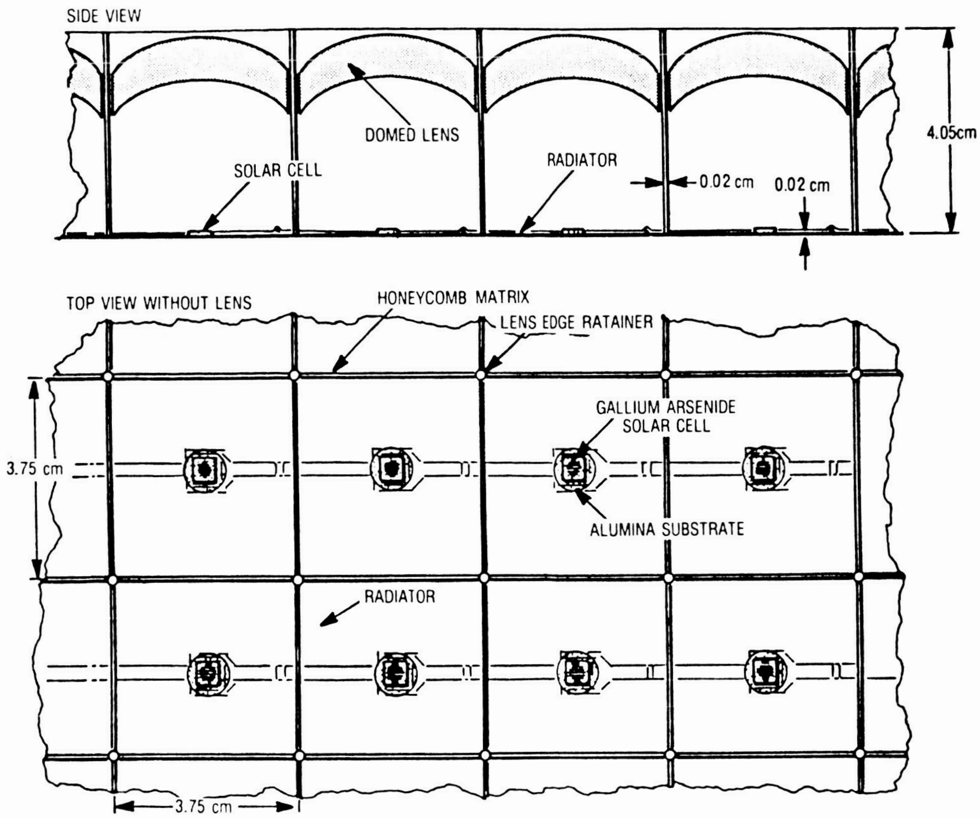


FIGURE 4

THREE DOME LENS PV PANELS

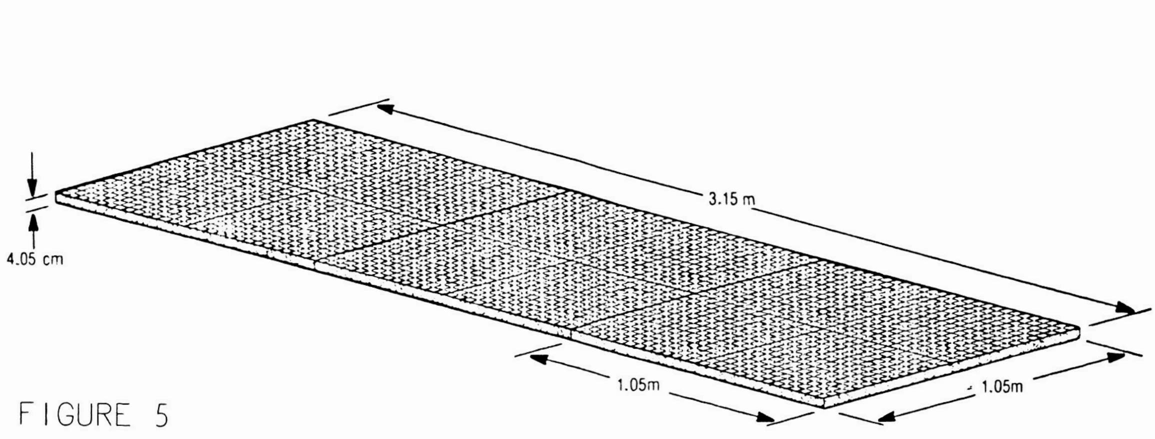


FIGURE 5

DOME LENS
PV ARRAYS ON ESS SYSTEM
ATTACHED TO SPACE STATION

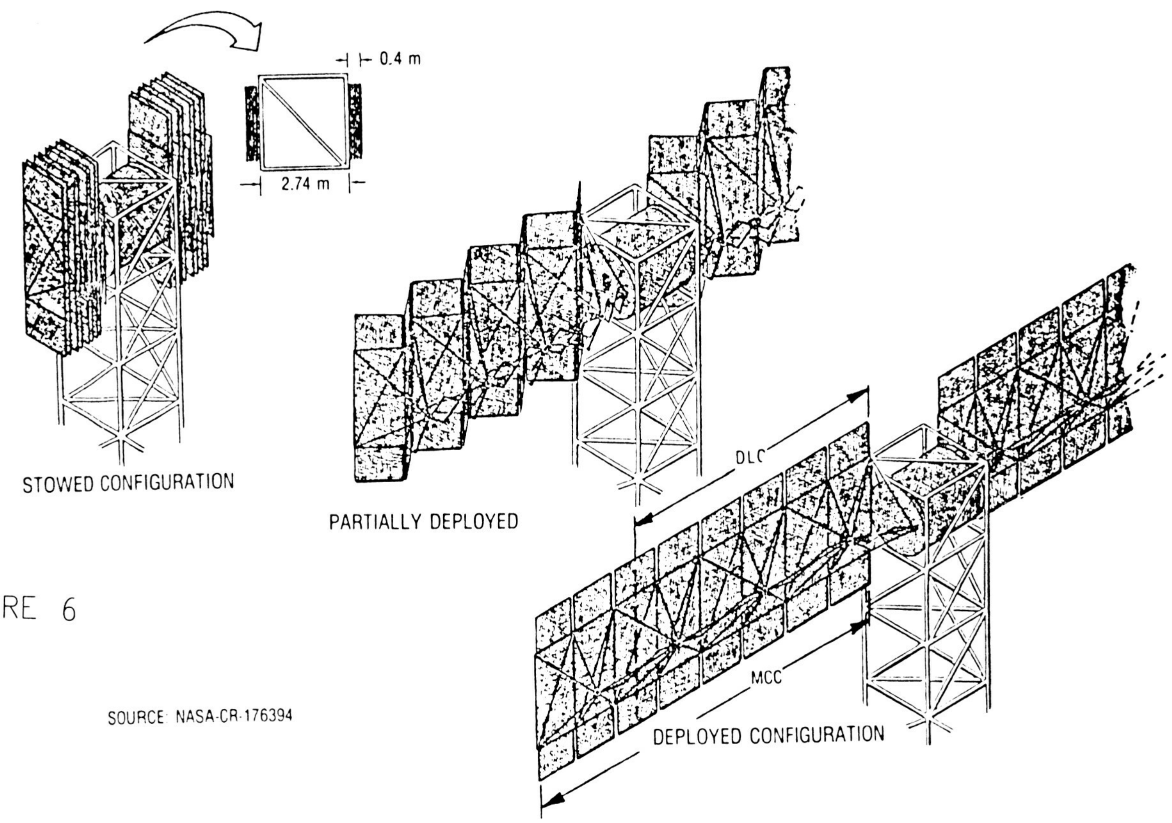


FIGURE 6

SOURCE: NASA-CR-176394

DOME LENS CONCENTRATOR (DLC)
PANEL WEIGHT ESTIMATE

FIGURE 7

PANEL COMPONENT	WEIGHT/PANEL AREA (KG/SQ.M.)
LENS	0.68
RADIATOR	0.54
CELL/MOUNT/INTERCONNECTS	0.05
ALUMINUM MATRIX	0.62
ATTACHMENTS	0.14
ADHESIVES	0.34
MISCELLANEOUS	0.13
TOTAL	2.50

SELECTED LENS DESIGN

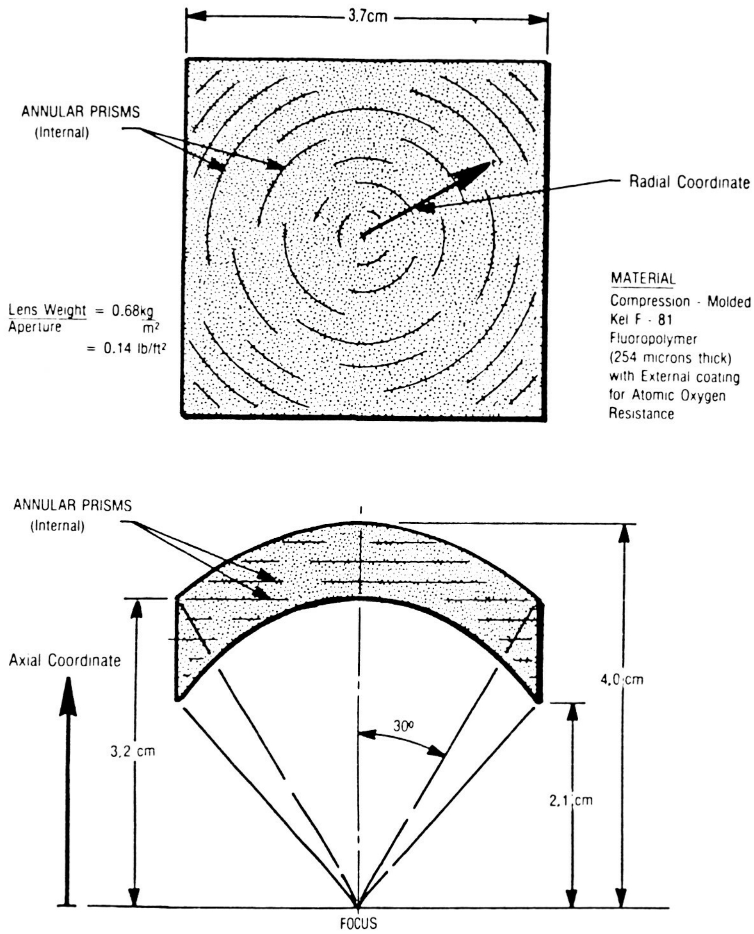


FIGURE 8

FLUX PROFILE FOR THE SELECTED SQUARE DOME LENS
DESIGNED FOR 1 DEGREE TRACKING ERROR GUARD BAND

HIGHEST BAR REPRESENTS 386 SUNS.

NOTE: FLUX VALUES ARE CIRCUMFERENTIAL AVERAGE VALUES, SINCE FLUX PROFILE FROM SQUARE LENS IS NOT PERFECTLY AXI-SYMMETRIC.

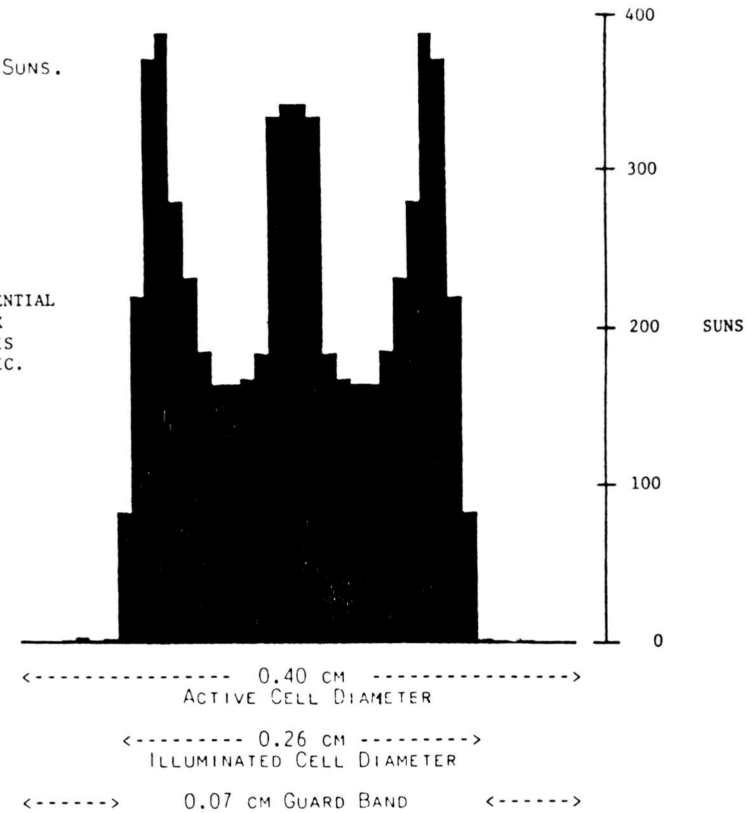


FIGURE 9

SELECTED 100X GALLIUM ARSENIDE CELL
FOR USE WITH ENTECH DOME LENS CONCENTRATOR
AND WITH ENTECH PRISMATIC CELL COVER

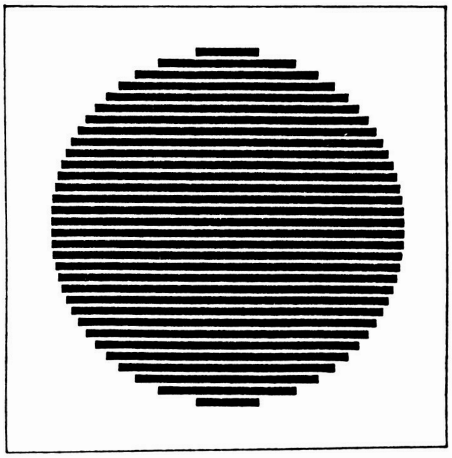
FIGURE 10

CELL GEOMETRY

TOTAL AREA: SQUARE, 0.5 CM PER SIDE, 0.2500 SQ.CM. AREA
ACTIVE AREA: CIRCLE, 0.4 CM DIAMETER, 0.1257 SQ.CM. AREA

METALLIZATION PATTERN (SHOWN IN WHITE)

NO. OF GRIDLINES:	31
GRIDLINE CENTERLINE SPACING:	127 MICRONS
GRIDLINE WIDTH:	25 MICRONS
GRIDLINE HEIGHT:	10 MICRONS
BUSBAR AROUND CELL PERIPHERY	



ELECTRICAL CHARACTERISTICS (@ AMO, 100 SUNS, 25 C)

PARAMETER	UNIFORM ILLUMINATION	LENS ILLUMINATION
ISC:	0.415 AMP*	0.415 AMP*
VOC:	1.154 VOLTS	1.154 VOLTS
FF:	0.877	0.852
EFFICIENCY:	0.247	0.240

*WITH PRISM COVER; 0.332 AMP WITHOUT COVER.

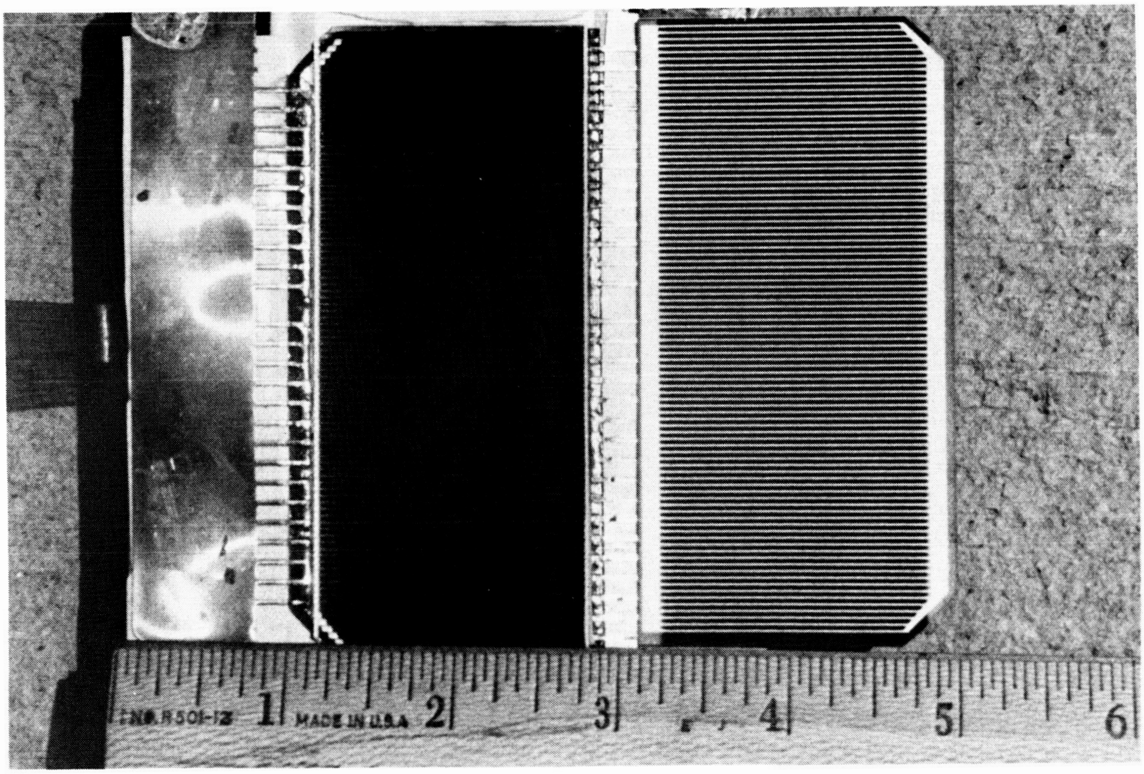
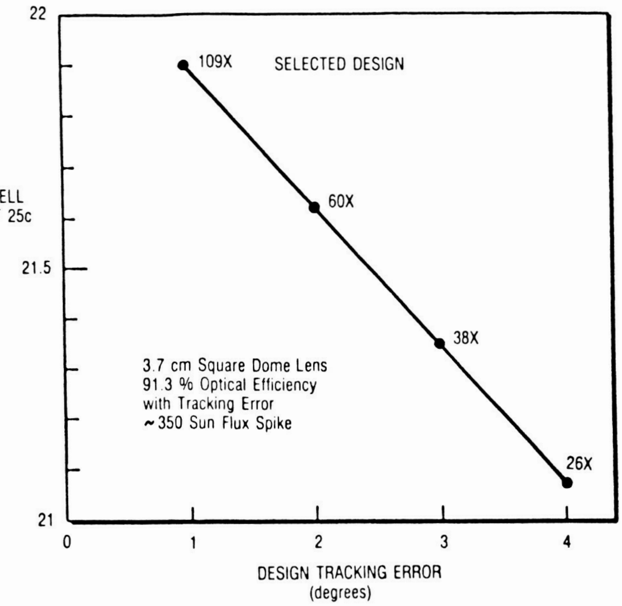


FIGURE 11 - EFFECTIVENESS OF ENTECH PRISMATIC CELL COVER FOR A 25% METALLIZED TERRESTRIAL SILICON CONCENTRATOR CELL

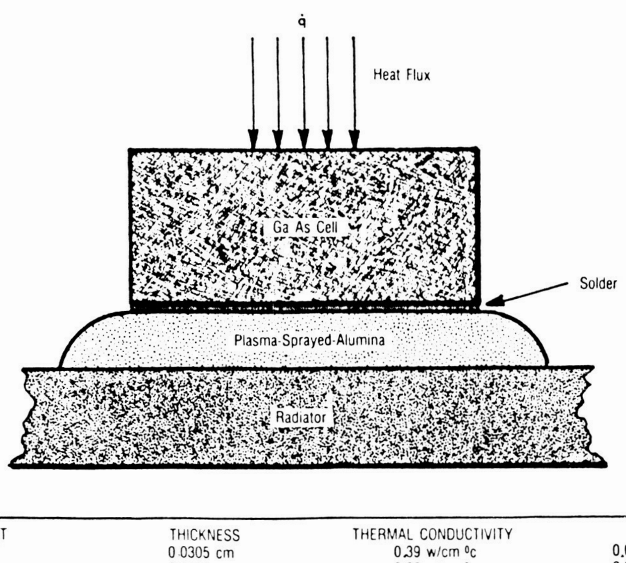
TRACKING ERROR TOLERANCE WITH VARIOUS CELL SIZES — ALL USING THE SELECTED LENS DESIGN

FIGURE 12



CELL MOUNT THERMAL ANALYSIS

FIGURE 13



ELEMENT	THICKNESS	THERMAL CONDUCTIVITY	t/k
Cell	0.0305 cm	0.39 w/cm °c	0.078 cm²·°c/w
Solder	0.0025 cm	0.32 w/cm °c	0.008 cm²·°c/w
Alumina	0.0127 cm	0.35 w/cm °c	0.036 cm²·°c/w
Radiator	0.0102 cm*	1.73 w/cm °c	0.006 cm²·°c/w
		TOTAL	0.128 cm²·°c/w

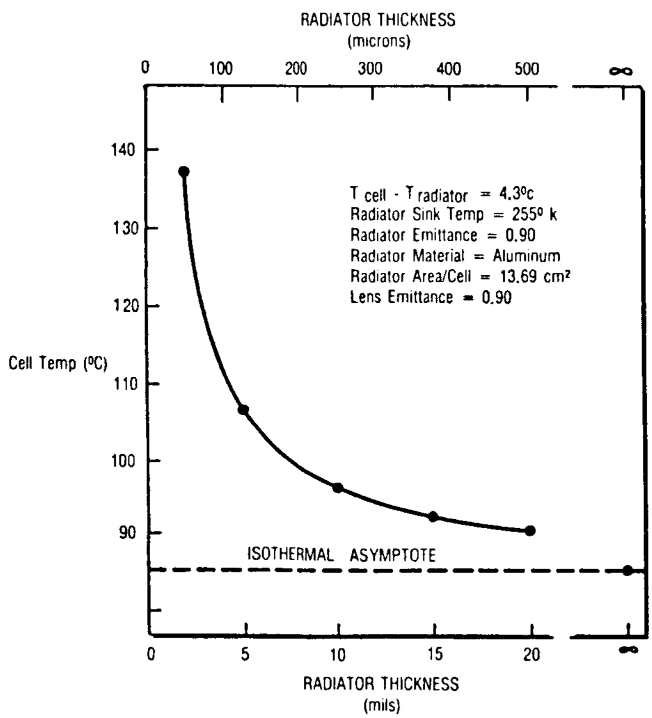
$\dot{q}$ = 350 suns * 0.1353 w/cm² * (0.95 - 0.24) = 33.6 w/cm²

$T_{cell} - T_{radiator} = \dot{q} * t/k = 4.3°c$

* ½ thickness of radiator, since heat radiates from both sides, and average radiator temperature is of interest.

RADIATOR THERMAL ANALYSIS RESULTS

FIGURE 14



RADIATOR THICKNESS SELECTION

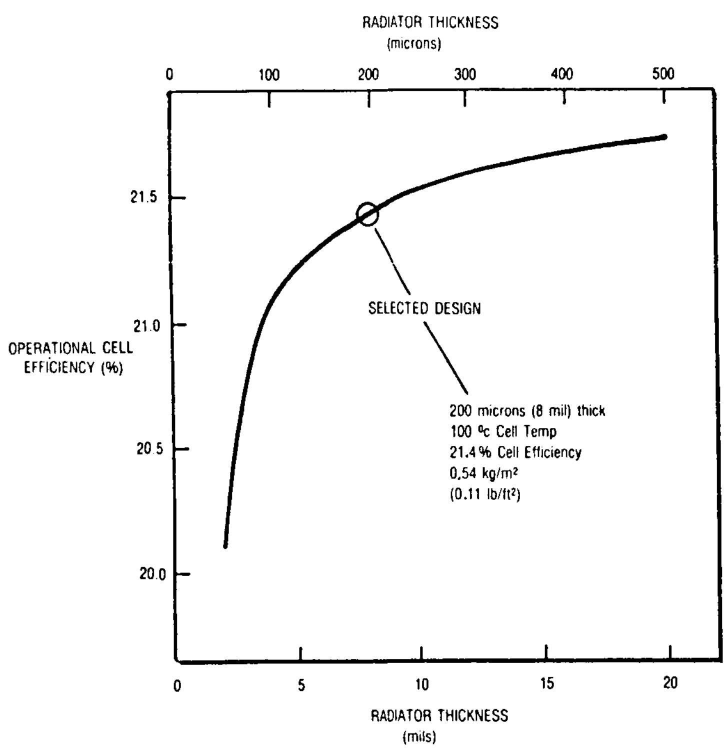


FIGURE 15

PERFORMANCE COMPARISON OF THREE COMPETING
TECHNOLOGIES FOR SPACE PHOTOVOLTAIC POWER

ITEM	LOCKHEED SPACE STATION* FLAT SILICON ARRAY (1 Sun, 20 C Cell)		TRW MINI-CASSEGRAINIAN** GaAs CONCENTRATOR ARRAY (100 Suns, 85 C Cell)		ENTECH DOME LENS GaAs CONCENTRATOR ARRAY (100 Suns, 100 C Cell)	
	Current	Improved	Current	Improved	Current	Improved
Cell Oper. Effy.	13.4%	14.6%	18.9%	21.2%	21.4%***	24.0%***
Optical Effy.	100.0%	100.0%	70.0%	80.0%	91.5%	96.0%
Packing Factor	96.0%	91.0%	88.0%	88.0%	97.0%	97.0%
Mismatch/Wiring	93.0%	93.0%	93.0%	93.0%	93.0%	93.0%
Array Efficiency	11.8%	12.4%	10.8%	13.9%	17.7%	20.8%
Watts/Sq.M.	160	168	146	188	239	281
Panel Kg/Sq.M.	N/A	N/A	5.7	5.7	2.5	2.5
Structure Kg/Sq.M.	N/A	N/A	0.7	0.7	0.7	0.7
Array Kg/Sq.M.	3.0	3.0	6.4	6.4	3.2	3.2
Watts/Kg	53	56	23	29	75	88

* R.V. Elms, LMSC, "Solar Arrays for Space Station and Platforms," IECEC-86, August 1986.

** R.E. Patterson, TRW, "Design, Performance Investigation, and Delivery of a Miniaturized Cassegrainian Concentrator Solar Array," Final Report, NASA Contract NAS8-35635, May 1985.

*** Cell performance using ENTECH's prismatic cell cover to eliminate gridline obscuration.

FIGURE 16